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Liquefaction of the Enmedio Island Soil Deposits

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SYNOPSIS. The results of field testing and of simplified liquefaction analyses of the Enmedio Island soil deposits are presented and discussed in this paper. It is found that for this case history simple criteria for assessing liquefaction potential yield results in accord with field behavior.

INTRODUCTION

On March 14, 1979, a 7.6 Richter magnitude earthquake with epicenter located in the Pacific Ocean, about 50 km off the coast of the state of Guerrero, Mexico, caused damage ranging from severe to light at distances over 350 km (i.e. Mexico City).

During the earthquake, the Enmedio Island soil deposits liquefied. The phenomenon was observed only at the South and Southwest zones of the island (zone 2, fig 1), which is located at the mouth of the Balsas River; its stratigraphy is composed of typical deltaic deposits, mainly, sand, gravelly sand, silt and mixtures of them.

Prior to the earthquake ocurrence, geotechnical studies were performed at the North and Northeast of the site (zone 1, fig 1); with this information a liquefiable sand stratum was identified, and it was suspected that this layer could extend into the zone which actually liquefied. A second site boring exploration program carried out after the seismic event at zone 2 showed that the sand stratum was also present in this zone.

A description of the earthquake effects, soil deposit characteristics and field detection of the liquefied sand layer is presented in this paper.

SITE CHARACTERISTICS

Geology

The Enmedio Island is located between the state of Guerrero and Michoacan, Mex. at the mouth of the Balsas River in the physiographic province of Sierra Madre del Sur.

According to Gutierrez (1971), the main features of the Balsas River delta are: irregular boundary between pre-deltaic rocks and the delta sediments; alluvial fans; ancient wandering of the River bed; wide flood plains; and marginal lagoons.

The deltaic sediments in the Enmedio Island are composed of sandy and silty soils down to 40 to 50 m deep, which are the product of eroded igneous, sedimentary and metamorphic pre-deltaic rocks. Mineralogical studies revealed that the upper ten meters of sandy soils consist of: quartz (50%), rock fragments (7%); dark minerals (10%), feldspar (25%), mica (0-3%), seashells and fragments (0-6%).

Seismicity

The Enmedio Island is located in a highly seismic zone associated with the subduction of the Pacific Ocean plate under the American Continent.

According to the results of a seismic risk study carried out by Esteva et al (1973), a seismic event of magnitude 8 can occur near by the site producing accelerations of 0.27 g and 0.35 g for recurrence periods of 100 and 500 years, respectively.

The earthquake of March 14, 1979 had a 7.6 magnitude and its epicenter was located in the Pacific Ocean some 50 km from the site, and its depth fixed at 59 km. The maximum ground acceleration recorded at SICARTSA steel mill, which is across the Balsas River, was about 309 cm/s^2. The duration of the event was 35 s, of which, the strongest part lasted 15 s.

The recording accelerometer is founded on an alluvial deposit 40 m deep, having similar characteristics to those encountered in the site.

Stratigraphy at the North Part of the Island

Several years before the March 14, 1979 earthquake occurred, the Balsas River was dredged and the waste product dumped at the North part of the Island. This resulted in a hydraulic fill with irregular thickness (2 m at most). Cobbles, gravels and coarse sand deposited at the North of zone 1 whereas finer products settled towards the center of the Island.

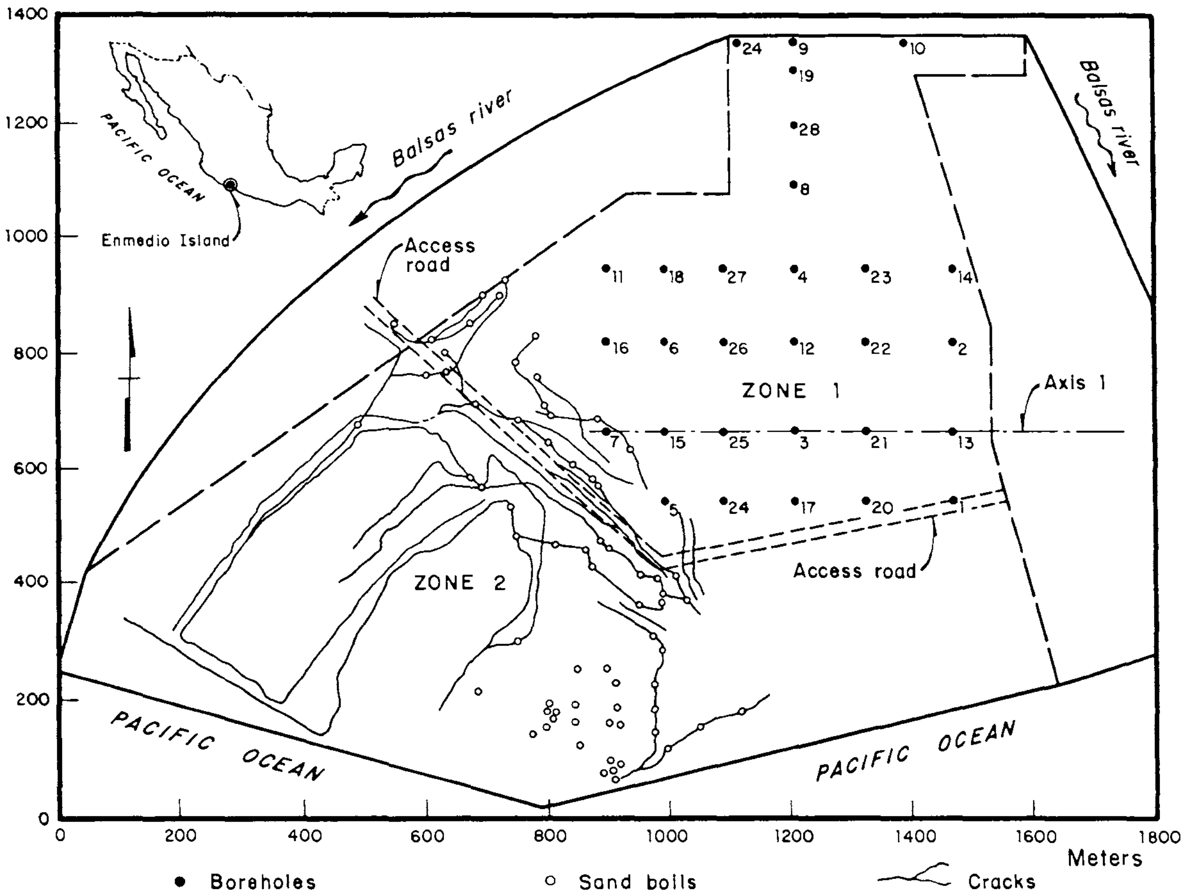

Fig 1. Plan view of the site. Boring location and observed damage cracks and sand boils

A compacted fill was placed on these deposits; the elevation reached to the northern side of the access road (fig 1) was 3.60 m, and an elevation of 1.2 m to the southern side. These elevations corresponded to the actual ground level during the seismic event.

Prior to the earthquake occurrence an exploration program, which included standard penetration tests (SPT) and sampling with Shelby tubes, was carried out (fig 1).

The stratigraphic profile along axis 2 (fig 1) is presented in fig 2. A stratum of dark gray fine sand ranging from loose to medium dense, with less than 15% of fines, is found throughout the profile. The thickness of this layer ranges from 1 to 6 m and is underlain by a series of strata composed of gravelly sand, sand and gravels, silty sand, silty clay and silty sands. The number of SPT blows on this strata sequence was greater than 40.

The ground water was at elevation 0.0 m when the earthquake occurred.

Soil Behavior

During the seismic event cracks (5 to 10 cm wide) and sand boils (0.3 to 1.5 m in diameter) developed at zone 2, fig 1. Many of the cracks were observed along the access road in the section NW-SE. Perpendicular to these cracks a different cracking pattern developed as shown in fig 1. Due to the cracking two columns of a building under construction tilted. On the other hand, most of the sand boils occurred at the Southern part of the Island. It was also observed that some boils were associated with cracks.

According to an eyewitness, the sand volcanoes appeared just before the shaking ended, and the jets of the sand-water mixture expelled reached a height of about 2 m. Few minutes later the flow and height of the jets were negligible, although water kept flowing for approximately 1½ hours after the end of the earthquake. The material expelled throughout the sand boils and some of the cracks was the dark gray, fine sand found at elevations 0.0 to -6.0 m.

Potentially Liquefiable Sand Stratum

From the stratigraphic information of the Northern part of the site (zone 1) together with the characteristics of the soil ejected from the volcanoes and cracks, it was concluded that the layer of dark gray fine sand was also present in the southern part of the Island where liquefaction occurred.

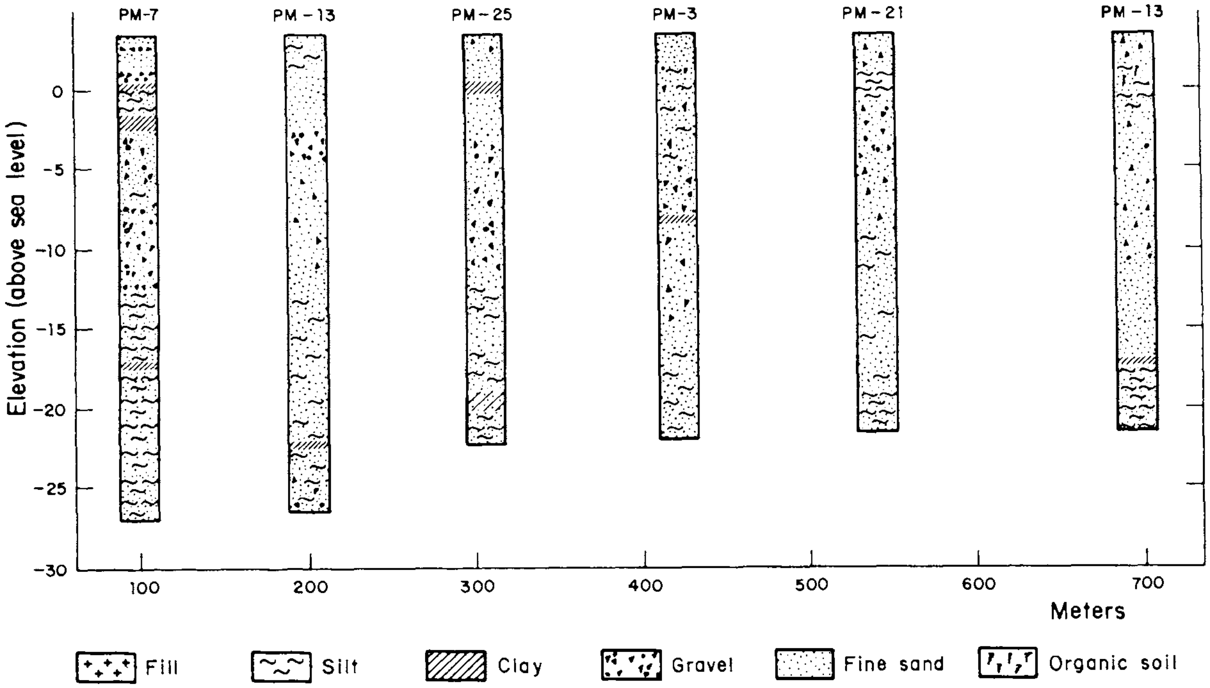

Fig 2. Stratigraphic profile along axis 1

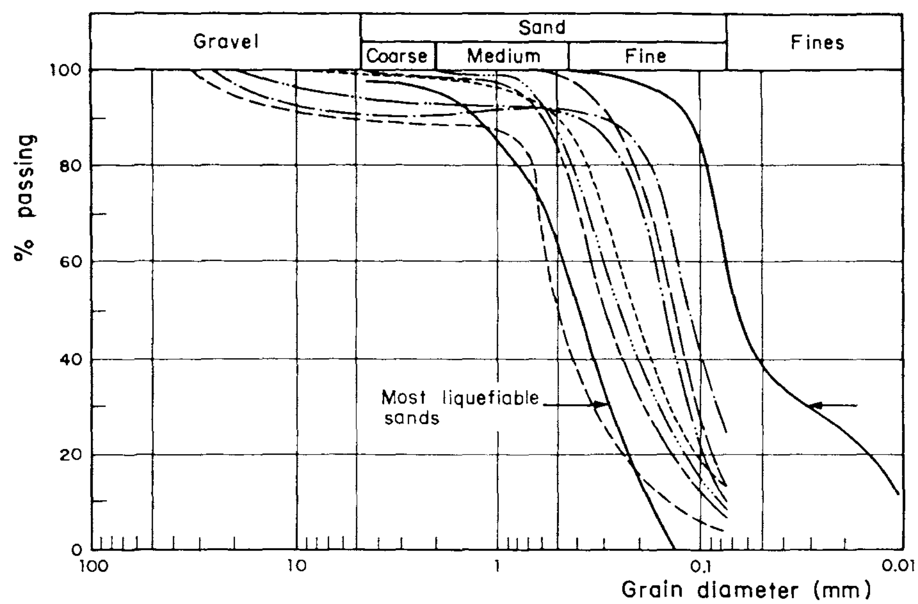

Fig 3. Grain size distribution curves. Liquefiable sand

Analyzing the grain distribution curves of the dark gray sand (fig 3) in zone 1 the following features are observed:

a) 0.074 mm < D_{50} < 2 mm

b) C_u < 10 (Uniformity coefficient)

c) Fines content 5 to 15%

On the other hand, the geometric characteristics of the soil deposit and the SPT results can be summarized as follows:

a) The layer thickness (h) of the soil overlying the sand stratum varies between 3.5 and 6.5 m.

b) The ratio of thickness h to sand layer thickness (H) is in average less than 1.

c) Taking into account the mean value of the minimum and maximum SPT results of each boring in the sand layer, the following values were obtained: $\bar{N}_{min}$ = 9 and $\bar{N}_{max}$ = 28, with variation coefficients CV_{min} = 0.53 and CV_{max} = 0.39. These values correspond to a loose to medium dense sand.

d) $\bar{N}_{min}$ is less than the product 2 h = 10 m.

From the results described, according to Kinshida's and Ohsaki's criteria (cited by Shanon & Wilson and Agbabian-Jacobsen Associates, 1971) it was concluded that the dark gray layer of sand, found in the North of the site was liquefiable.

On the basis of the above mentioned results, a second exploratory boring program was carried out in the zone which exhibited liquefaction (zone 2), with the purpose of having a more detailed stratigraphic information of the area.

ADDITIONAL SITE EXPLORATION

The location of the borings for the field exploration which is shown esquematically in fig 4 consisted of: standard penetration tests (14), boring combining SPT and Shelby tubes to elevation -21 m (12), pressuremeter tests (4), Lefranc permeability tests (2); and two open pits.

Stratigraphy

At the Southwest of the site the ground level was at elevation +1.2 m; from this level down to 0.0 m the soil consisted of a yellowish silty sand medium to fine. Close to elevation 0.0 there was a silty clay layer 40 cm thick.

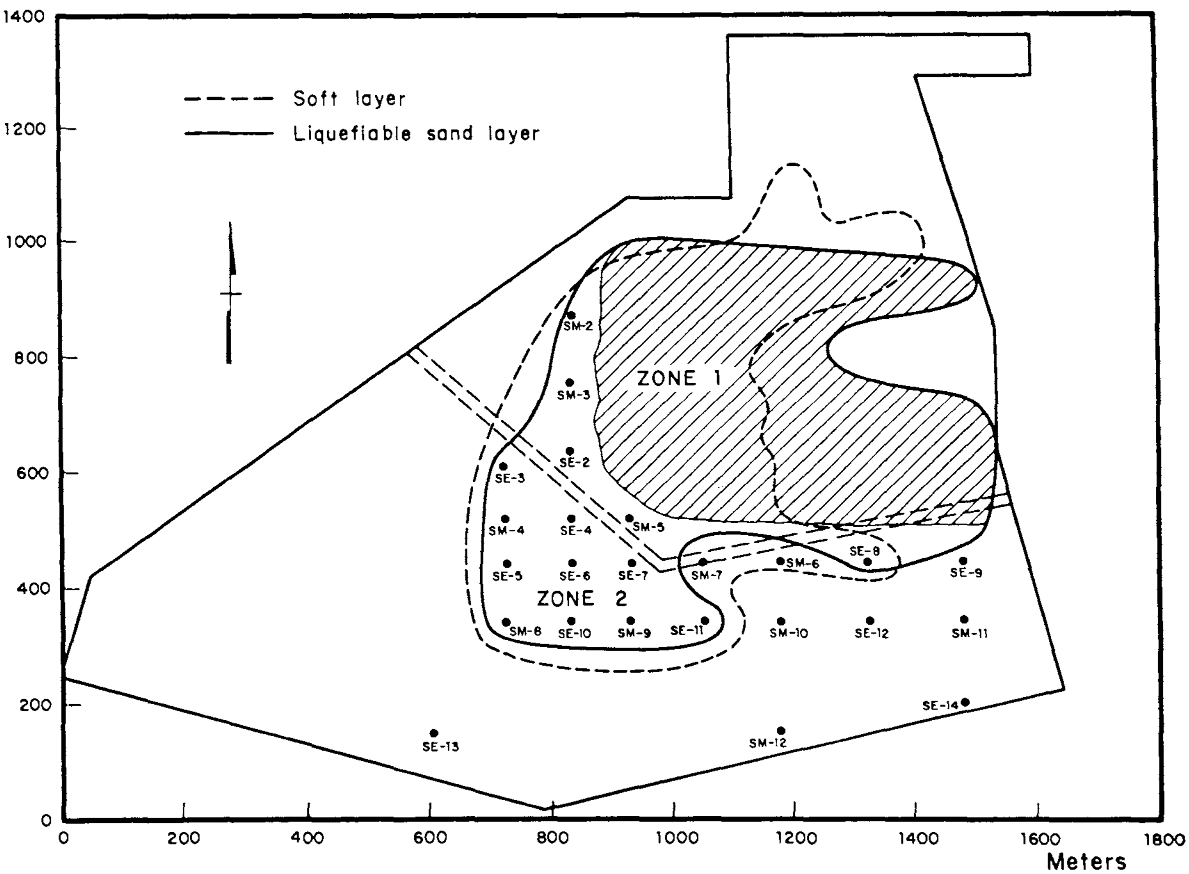

Fig 4. Additional site exploration

The boring studies carried out revealed that stratigraphy at zone 2 was very similar to that found in the Northern part of the Island (fig 2). The layer of dark gray fine sand was also found at elevations 0.0 to -1.80 m with thickness varying from 1.5 to 5 m, and fines content less than 15%, it exhibits a minimum SPT mean value $\bar{N}_{min}$ = 10 blows and a maximum $\bar{N}_{max}$ = 22 with CV_{min} = 0.37 and CV_{max} = 0.19. As before from elevation -7.5 m below the soil is dense with SPT values greater than 40 blows.

Pressuremeter Tests

Nine tests were performed in 4 boreholes located close to the borings shown in fig 4. Four tests were made in the dark gray sand stratum obtaining a limit pressure p_ℓ between 1.9 and 3.95 kg/cm^2 and Ménard modulus of deformability E_s = 15 - 20.5 kg/cm^2. According to Centre D'Etudes Geotechniques de Paris (1972), these values correspond to a medium to loose sand.

Lefranc Permeability Tests

The Lefranc permeability tests gave the following data: $k = 6.4 \times 10^{-3}$ cm/sec for the gray sand layer; $k = 8.11 \times 10^{-2}$ cm/sec for the gravelly sand stratum underlying the sand; $k = 1.8 \times 10^{-4}$ cm/sec for the silty clay layer overlying the dark gray sand.

LIQUEFACTION EVALUATION

Characteristics of the Sand Layer

In table I are presented the main characteristics of the dark gray sand encountered throughout the Enmedio Island. These results include both site exploration programs.

TABLE I. Description of the Dark Gray Sand

Particle size	$0.1 < D_{50} < 0.50$ mm $2.43 < C_u < 3.92$
Grain shape	angular
Minerals	Quartz (50%), feldspar (25%) ferromagnesians (10%), rock fragments (7%), mica (0-3%) seashells (0-6%)
Bounding	There is no trace of bounding neither by carbonation nor by oxidation

On the basis of grain distribution curves, stratigraphic profiles and SPT results, the spatial distribution of the liquefiable sand layer was determined (fig 4). The upper part of the layer is found at elevations 0.0 and -2.0 m, with a mean elevation of -0.25 m. Its thickness varies between 1 and 6 m, having an average of 3.40 m.

Overlying the sand layer there is an impervious stratum having an average thickness of 0.70 m and composed of clay (CH) with lenses of silt (ML). Its spatial distribution is also shown in fig 4.

Below the sand stratum there is a layer of gravelly sand and sandy gravel.

The statistical SPT results obtained in zones 1 and 2, for the sand layer are shown in table II.

TABLE II. SPT. Results in zones 1 and 2

Statistical value	Sand layer zone 1	Sand layer zone 2
$\bar{N}_{min}$	12	10
σ_{min}	5.58	3.92
CV_{min}	0.45	0.38
$\bar{N}_{max}$	27	21
σ_{max}	8.29	4.98
CV_{max}	0.30	0.24
$\bar{N}_{av}$	20	16
σ_{av}	5.16	3.95
CV_{av}	0.26	0.25

The average mean values ($\bar{N}_{av}$) were obtained taking into account all SPT test results, obtained in each boring within the corresponding zone.

Eventhough there is a small difference in SPT values between zones 1 and 2, it can be observed a consistent trend showing higher values in zone 1. This is due to the fact that the overburden pressure in the sand layer of zone 2 is lower than that of the zone 1, because of the differences existing in ground level elevations. The stress profiles for both zones are shown in fig 5.

Liquefaction Susceptibility Analysis

Using the SPT results shown in table II, the stress profiles of fig 5, the maximum ground acceleration estimated from the records at SICARTSA steel mill (0.3 g) and the simplified criterion proposed by Seed et al (1975), the liquefaction susceptibility analysis was carried out. The results obtained are summarized in table III and plotted in fig 6.

TABLE III. Susceptibility to liquefaction of the Dark Gray Layer of Sand

Parameter	Zone 1	Zone 2
Total stress σ_o (kg/cm^2)	1.0	0.55
Effective stress $\bar{\sigma}_o$ (kg/cm^2)	0.8	0.4
$\bar{N}'_{min}$	13	15
$\bar{N}'_{max}$	30	31
$\bar{N}'_{av}$	22	24
$\tau/\bar{\sigma}_o$	0.23	0.26

In this table

$$\bar{N}' = C_N \cdot \bar{N}$$

$$C_N = 1 - 1.25 \log \frac{\bar{\sigma}_o}{\sigma_1}$$

$$\sigma_1 = 1 \text{ kg/cm}^2$$

$$\frac{\tau}{\bar{\sigma}_o} = 0.65 \frac{a_{max}}{g} \frac{\sigma_o}{\bar{\sigma}_c} r_d$$

a_{max} maximum acceleration on the ground surface

r_d - stress reduction factor (it was considered 0.95)

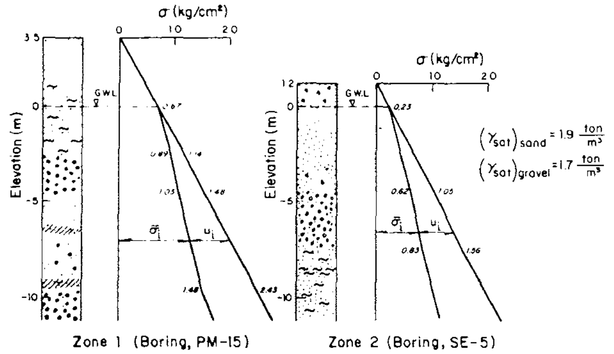

Fig 5. Soil stress distribution in zones 1 and 2

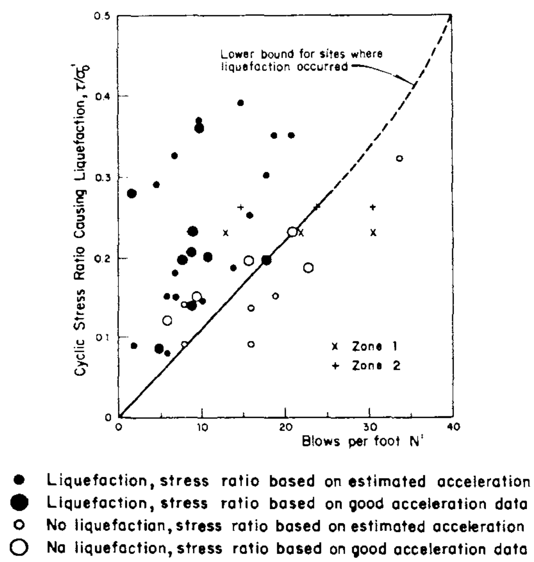

Fig 6. Correlation between stress ratio causing liquefaction in the field and penetration resistance of sand (Seed, 1979)

From this figure it is seen that the points corresponding to $\bar{N}'_{min}$ of both zones lie in the liquefiable part, the $\bar{N}'_{av}$ values fall on the borderline and the $\bar{N}'_{max}$ values fall on the non-liquefiable part.

According to these results it is concluded that the dark gray layer of sand in both zones is liquefiable or at least it is in the borderline. Since the sand layer actually liquefied in zone 2; there remains to be answered why zone 1 did not show signals of liquefaction. This is the main subject of a companion paper to this conference, in which the results of cyclic triaxial tests and of analyses of pore pressure generation and dissipation during the earthquake are presented, Jaime, Romo and Montañez (1931)

FINAL COMMENTS

On the basis of the results of this investigation several conclusions can be drawn:

a) Empirical criteria (such as Ohsaki's and Kishida's) based on geometric characteristics of the soil deposit, SPT results and grain distribution of the material, can be very useful to detect liquefiable soils on preliminary basis.

b) Seed's empirical correlation gives a good estimate of the susceptibility to liquefaction. Eventhough, it seems that the borderline of fig 6 could be drawn a little further to the right.

c) There remains to be answered why zone 2 liquefied and why zone 1 did not.

ACKNOWLEDGMENTS

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